STARDUST: Discovery's InterStellar Dust and Cometary Sample Return Mission

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1. INTRODUCTION

The *Discovery* Program is about a new way to continue the legacy of the Mariners, Voyager, Magellan, and Galileo in deep space exploration. *Discovery* is changing the way NASA does business. It is a central element in a *complete culture change* for planetary exploration and space science. Discovery's goal is to achieve results *faster, better,* and *cheaper*. It will be more effective, do more with less- specifically, carry out planetary flight missions with highly constrained total cost. STARDUST was selected from a pool of 28 proposals in 1994. It becomes the 4th mission in the series following: Near Earth Asteroid Rendezvous (NEAR), Mars *Pathfinder*, and Lunar *Prospector*.

Historically, planetary missions evolved to large, complex platforms with up to 14 scientific experiments and price-tags of up to $2 Billion. These missions endeavored to do remote-sensing and in-situ investigations on extremely stringent diets of power, mass, and volume. The struggles in the scientific community to one of the selected experiments were difficult and frustrating.

STARDUST proposes to exactly *reverse* the paradigm. It is a *sample return* mission whose fundamental premise is to bring the essence of the solar system, material from a comet, home! With samples back on Earth, literally *hundreds* of experimenters can participate. They can apply already-existing instruments with relatively unlimited power, mass, and volume constraints currently located in the finest labs and universities. This will allow participation in solar system exploration by a broad community. And the opportunity is offered at a *Discovery* price of less than 10% of the traditional approach!

STARDUST plans the *first* return of material from a solar-system body since the *Apollo* and *Luna* sample-return missions of the 1970s. But, more importantly, the *first of all time* from beyond the Earth-Moon system. As such it becomes a model for planning follow-on sample-return missions to other planetary bodies. The simplicity and compactness of the Sample Return Capsule (SRC) should be very attractive to follow-on applications. Fig 1. shows the STARDUST spacecraft in its sampling configuration.

Fig. 1. The STARDUST Spacecraft (Two Views)

The major features of the STARDUST flight system are 1) the SRC, about a meter in diameter shown open like a "clamshell" with the dust collector grid deployed into the dust stream above the so-called "Whipple shield;" 2) the shield consists of two plates with Nexel™ curtains between to stop the high-speed particles from impacting sensitive spacecraft elements; 3) solar-arrays, and 4) the Cometary and Interstellar Dust Analyzer (CIDA) to be provided by Germany. The flight system also carries a refurbished *Voyager* camera to provide optical navigation capability. The plan is to also use this camera for imaging the nucleus of the comet to a resolution an order-of-magnitude better than *Giotto* was able to image *Halley*.

The STARDUST Project operates on the Total Quality Management (TQM) principle of *concurrent engineering*, which saws time. improves communications, and reduce costs t ingingall elements together early.

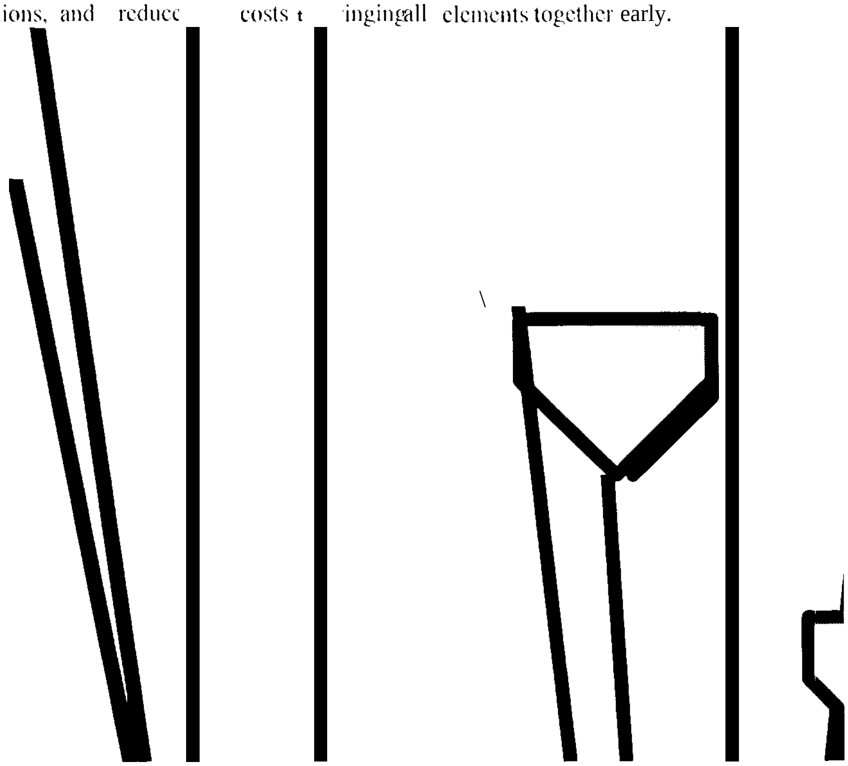

Fig. 2. Mission Testbed as an Evolutionary Integration Environment

The objective is to mitigate the traditional culture of *serial* processing of project elements.

2. Concurrent Engineering for Mission Success

Concurrent engineering means producibility. testability, and operab ility are fully considered in all phases. But how is this done'? More importantly, how is it done *efficientlly*? The key to success i s modern computer and communications technologies.

The STARDUST team has eng incered a common, collaborative server approach to provide a central repository o f all communication products. The products include drawings, presentations, memos, formal documents, spreadsheets, etc. This collaborative server environment brings visual access to all project players at their ol'lice workstations or in a conference room setting. With full, flexible video access to the products, it remained to ensure audio communications with equal user access and flexibility. This has been achieved with the leasing of a dedicated "meet-me" teleconference line. This audio dial-in access is available from virtually any telephone. Up to about 50 participants can access any meeting from sites anywhere. And with a portable computer that contains downloaded products from the server, both visual and audio involvement is achieved from any telephone. The impact has been to allow team members "just in time" involvement in meetings while working in their offices. This "virtual meeting room" environment has been put in place to save travel (even from office to conference mom), allow last minute and real-lime changes to products such as documents, presentations, spreadsheets, etc., and facilitate "spur-of-the-moment" meetings "in the server." Thus widely-separated team members at Lockheed-Martin in Denver and JPL in Pasadena can meet "virtually" and quickly on issues and have the full-repository of Project data and communication products available on screen.

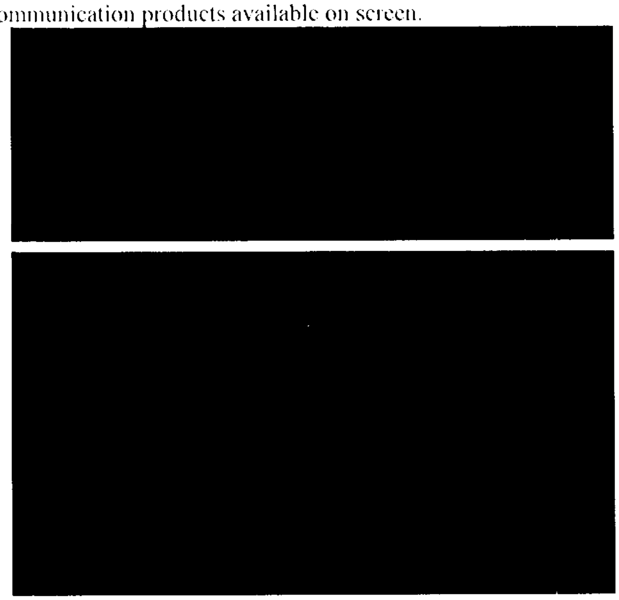

Figure (X): Integrated Team Management Structure

By placing a priority on communications with this cost-saving, user-f'ricadly technique, the STARDUST team is able to focus all elements in a concurrent engineering group called the *Project r:11'f;;tl('trill'q and Integration Team (PEIT)*. The PEIT meets weekly as a central forum for discussion and actions. It is led by the Project Engineer and comprised of such engineering leaders or cognizants of the key project elements such as trajectory engineer, and mission test system engineer. Here, cross-system issues are brought front-and-center. End-to-end information issues are being dealt with early in the development cycle such that the tradition of spacecraft first, and testability and operability sc'toad, is being broken. The PEIT focus is on teamwork. This involves everybody in the big-picture fundamental mission success metric, *return of cometary and interstellar material.*

The PEIT also involves, at the appropriate level, business functions, safety, and public outreach/education. It provides the central control forum for the principal investigator (PI) and project manager (I'M), providing an arena where performance and accountability in each element of the project is be highly visible. Figure (X) above depicts the concurrent engineering and management structure that "wraps around" the major project elements by operating in the flexible "virtual meetin g" communications environment.

Key to the successful achievement of the mission goals within the cost cap are the controls and processes applied by tbc PI and his management team. The key development process is the use of a central *mission test environment*, the *Stardust Miss ion Test System (SMTS)*, to bring all the elements together early in an cad-lo-cad environment. The idea of keeping the focus at a *mission* level is to faithfully serve the ethic derived from the famed Lockheed "Skunkworks" to reduce risks by "testing it like you fly it."

Fig. 2 shows the integrating role of the SM I S in getting at the mission interfaces early and iterating in phases of increasing interface complexity. This process, pioneered on the Mars *Pathfinder* mission, is aimed at discovering interface issues early, fixing them, and allowing a seamless, smooth transition in to the Assembly, Test, and Launch Operations (ATLO) portion of the project schedule.

Specifically, STARDUST will exploit capabilities provided by the *Spacecraft Technology Center* and *Spacecraft Test Laboratories* at LMA and the *Flight System Testbed* at JPL. Each of three product-accountable managers will deliver STARDUST-specific hardware and software at different levels of maturity to this mission integration environment.

The SM I'S plan is to include engineering development units (EDU's), so ftware, mission models, dynamic models, and, where possible, flight articles. This will provide the PEIT with real data, not paper, to validate the designs; control algorithms; and interfaces in a *mission/system* context as they arc produced by the design and fabrication elements at different phases.

'1 he primary "ethic" of the STARDUST Project is to develop the target low-risk *Integrated Mission Capability (IMC)*, e.g. lhc complete set of integrated and tested hardware, software, operational procedures, analysis procedures, and facilities to attain the fundamental *Mission Success* criterion, and operate it successfully within the baseline budget established with NASA. The IMC is *the* product of the manage-to-budget culture central to the project's continued viability.

2. STARDUST SCIENCE GOALS

2.1 Science Instruments

STARDUST carries only two dedicated science investigations: the aerogel dust collector and the Comet and Interstellar Dust Analyzer ((' I I) A). All other science **data** is obtained from engineering functions that are required for the operation of the spacecraft. 1 bcsc engineering instruments are the navigation camera and the Whipple-shield flux monitors. Dynamic science is obtained without special hardware.

2.1.1 *Aerogel Dust Collector.* '1 he dust collector will simply expose blocks of underdense, microporous silica aerogel and other low-density media to the sample flux. The collector will consist of modular aluminum cells housing 1. to 2-cm thick aerogel blocks, The cells will form a two-sided, grid-shaped array that will deploy from the SRC. One side of the array will collect comet particles and the opposite side, interstellar dust particles. The useful collecting area will bc about 1 000 cm^2 for each target sample. The density of impacts will bc low and this dual use will cause no problem with sample discrimination. The bulk of the array will be aerogel with an average density of 0.02 g cm ^{3}. The collector will bc totally inert and have only to be exposed and recovered.

Extensive experience exists in both laboratory and **spice** flights with aerogel for collecting hyper velocity particles [15, 16]. More than 2.4 m^2 of silica aerogel capture cells have been flown and recovered on Shuttle flights, Spacehab II, and Eureca

Silica aerogel has been shown to be more effective in capturing organic volatiles than activated charcoal [2], and physisorption of noble gases under a simulated cometary flyby encounter environment has proved surprisingly successful [14]. Additionally, each collector medium will bc doped with selected absorbents.

2.1.2 *Comet and Interstellar Dust Analyzer.* 'l'his is essentially the same instrument design that flew on Giotto and the two Vega spacecraft, obtaining unique data on chemical composition of individual particulates in I [al Icy 's coma. It consists of an inlet, a target, an ion extractor, a time-of-flig$t ('1 01') mass spectrometer (MS), and an ion detector. The inlet is baffled to prevent sunlight from entering tbc instrument and raising the background noise in the detector. The target is 50 c m^2 of corrugated silver or other heavy metal. A light flash which accompanies the initial impact sets the zero for the '1 OF measurement. Electrostatic grids extract positive or negative ions from the impact microplasma. These ions move down the beat-tahc TOF MS where an electrostatic reflector focuses ions of similar energies onto the ion detector. Measuring arrival time determines the **mass** of the ions. This instrument is sensitive over a range of 1 to 150 AMU. Even sub-μm sized particles will produce observable signals and compositional profiles.

2.1.3 Navigation Camera. The camera optics for STARDUST are spare Voyager wide-angle units. Plans also include a single Voyager eight-position filler wheel and thermal housing and a 1 024x 1024 charge-coupled device detector with 12-μm pixels. This will give 6-m pixel resolution at 100 km.

Shutter speed is 5 ms. Some image motion compensation is planned by moving the imaging scan mirror. This will improve the resolution to perhaps 5 m, an order of magnitude better than Giotto. Less dust opacity and the lower flyby speed (6 kms^{-1} versus 70 kms^{-1}) guarantee better and more comprehensive imaging of the nucleus.

2.1.4 *Whipple Shield Dust Flux Monitor.*

(Description to be Added)

2.2 Anticipated Science Return

The wealth of data which will result from the STARDUST mission is due to its multi-faceted nature. It will collect interplanetary dust and, with mission implementation optimized, it will also collect extra solar system grains, i.e. the interstellar dust. And while cometary samples are of intrinsic interest for the entire comet science community, they hold considerable interest for exobiologists as well.

2.2.1 *Cometary Dust.* Comets presumably formed in the outer solar nebula, where the temperature remained low enough that many intact interstellar grains (IGs) should have survived nebular processing [13]. At present it is not known what fraction of cometary dust is presolar, and what fraction was formed in the solar nebula and transported to the region of comet formation. It is also not known how the nebular accretion of IGs into larger aggregates may have changed their observable properties.

For comet samples that can be captured intact, it should be possible to determine the following:

(a) The mineralogical, elemental, and chemical composition of comets at the sub-μm scale.
(b) The extent that building materials of comets are found in interplanetary dust particles (IDPs) and meteorites.
(c) The state of water in comets whether in ice or in hydrated minerals.
(d) Mixing of inner nebular materials (i.e. chondrule fragments) to the comet formation region.
(e) The presence of isotopic anomalies
(f) The nature of the carbonaceous material and its relationship to silicates and other phases.
(g) Evidence for pre-accretional processing either in the interstellar medium or in the nebula (including cosmic ray tracks, sputtered rims, etc.).

2.2.2 *Cometary Volatiles.* Although the dust/volatiles ratio varies greatly from comet to cored, volatiles account for a significant fraction of the mass of every comet nucleus. Of special interest are the biogenic elements (C, H, N, O, P, and S) and their molecules. At the very least, the obtainable information on gaseous components will be elemental and isotopic. In addition, the CIDA carried on STARDUST will provide direct measurements of volatile species in the impacting dust samples and is expected to obtain much more information on complex molecules than for the Halley flybys because impacts with coma particles will be less than 100 times as energetic.

2.2.3 *Interstellar Dust.* At present, astronomically derived information on IGs comes primarily from observations of extinction. scattering, polarization, and infrared emission. While such astronomical observations provide clues to the nature of IGs, they are not sufficiently definitive to confidently match the particles with theoretical models. Basic information, such as the abundance of SiC (from carbon stars), the abundance of graphite, grain morphology. silicate mineralogy, the role of radiation processing, grain ages, and the association of silicates and carbonaceous matter, is highly uncertain. Collection of even a few degraded particles would provide a unique and historic opportunity to directly examine solid matter that formed outside the solar system. This information would provide powerful constraints on grain models and provide insight in the relationship of presolar and meteoritic materials.

It will be possible to determine:

(a) The elemental composition of the grains.
(b) The isotopic composition of several important elements, such as C, H, Mg, Si, and O.
(c) The mineralogical and textural character of surviving phases.
(d) Whether all IGs are isotopically anomalous.
(e) The mineralogy of the silicate grains- whether glassy or crystalline, as well as their Si:O ratio.
(f) The prevalence of graphite particles, including whether their abundance is sufficient to explain the interstellar 0.22-μm extinction bump.
(g) The extent of physical mixing of the mineral phases, including whether the grains have a silicate core/organic refractory mantle structure, and also if they are a heterogeneous mixture or not.
(h) Whether there is any evidence for grain processing in the interstellar medium, especially whether the effects of shock sputtering, collisions, accretion, and chemical alteration can be identified.

STARDUST will provide ground truth on interstellar grain models and perhaps reveal physical properties and effects of processes that were previously unforeseen. It will provide data on the degree of processing after initial formation in circumstellar regions, and it will provide information on the relative importance of oxygen-rich and carbon stars in producing interstellar dust. Isotopic ratios in the samples will yield information on nucleosynthetic processes in a variety of stars. In the case of hydrogen, isotopic fractionation will provide insight into the ion-molecule reactions that are a favored explanation for high Deuterium/Hydrogen ratios in some molecular clouds and trace components in meteorites and IDPs.

2.2.4 Exobiology Implications. Comets are now known to contain large quantities of volatiles, including organic compounds and a rich variety of microparticles of various types (pure organic particles, silicates, sulfides, and mixed particles) with a graduation of sizes that extends to sub-μm diameters. With high surface areas, juxtaposed chemical constituents, and their easy transportability, these particulates may have been critically important for abiotic catalytic activity, macromolecular synthesis, and subsequent chemosynthetic pathways **[5,6]. '1** hcsc are thc well-known prerequisite processes for thc origin of life.

Comets, being rich in water and othei volatiles, have been postulated to bc transporters of volatile and biogenic elements to the early Earth. Clearly, the study of cometary material is essential for understanding the formation of the solar system. and, most importantly to exobiology, the interstellar contribution **of** pristine, eai ly-formed oi ganic matter from several different environmental regions. I low the biogenic elements entered the solar system, were transformed by processes operating therein, became distributed among planetary bodies, and what molecular and mineral forms they took during this history are questions of major importance for exobiology. Compai ison of the compositions of the volatiles contained w ithin cometary material with those found in carbonaceous meteorites and interplanetary dust will provide a basis for determining what commonalties in source regions can be attributed to the materials in these putatively related objects. '1 hc analysis of minerals like carbon ates, clays, and sulfates in comet dust **will** also be significant for the history of interaction between water and minerals in the early solai system [4].

3. STARDUST MISSION DESIGN

3.1 Trajectory

S 1 AR D UST's seven-year, three loop, AVEGA (Earth gravity assist) trajectory **is** designed (1) to fly by Wild **2** at **a 10l%** velocity while it is active, (2) to maximize the time for favorable collection of interstellar dust, and (3) to minimize the C_3 (escape energy from Earth) and AV requirements for the mission so that a small launch vehicle may be used. Fig. 3 shows the spacecraft trajectory and the location of Earth, Wild 2, and the deep space maneuvers **(m** orbit.

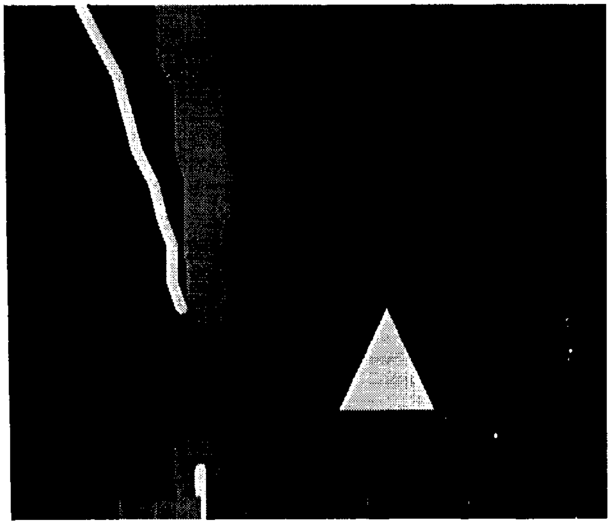

Fig. 3. STARDUST Trajectory (E-E-Wild **2-** E)

'1 bc S1AR DUST spacecraft will be launched in February 1999. The first orbital loop is a 2-year AVEGA path with a 171 Ills' AV neai aphelion. '1 his AV will set up the Earth sw ingby that will pump the orbit up to the 2.5-year loop, which the spacecraft will fly twice. At 160 days before encounter, a small AV of 66 ms^{-1} will set up the Wild 2 flyby. '1 his will occur **011 I** Jan 2004, at 1.86 AU and 97.5 days past

Table 1. Propulsion and Flight System Parameters

Wild 2 perihelion passage. The spacecraft will approach the comet at 6.2 kms^{-1} from sunside with a 70° **phase** angle. Coma fly-through will be on the sun side at a miss distance of 100 km. Flyby is five years after launch, and Eai th return, two years later.

Interstellar dust will be collected on two of the three post-apheli on legs of the orbits, where the spacecraft orient ation makes it possible to collect IGs at low velocity. In these portions of the orbit, indicated by ISP 1 & 2, the vectors of the IGs and the spacecraft align favorably to yield lower relative velocities.

3.2 Flight System Performance

Table 1 shows propulsion parameters and launch capability for the baseline launch energy requirement of 26 km^2s^{-2},.

3.3 Wild 2 Encounter Phase Design

5'..3.1 *Wild 2 Encounter Geometry.* The spacecraft will encounter Wild 2 at 97,5 days past perihelion at 1,85 AU from Sun when Wild 2 is far from its peak active period and relatively safe for a close flyby. The spacecraft will approach Wild 2 from above its orbital plane, then dip slightly below it. Fig. 4 shows the geometry of the flyby, which will be at 100 km on the sun side,

Investigations of the navigation accuracy and tbc impacts (m the entire encounter profile is based on this aim point and is regarded as a worst-case analysis. Final selection of the aim point may be further out and the encounter date may be shifted depending on the results of the ground observations of Wild 2 in early 1997.

3.3.2 Navigation Plan. STARDUST will usc both radio and optical navig ation (OPN AV). Early knowledge of the orbital state of Wild 2 bawd on ground observations gives an estimated position uncertainty of about 1500 km (1σ). An improvement over this is expected at about E- 50 days, after OPNAV has been in operation for some time. The adopted navigation plan can deliver with an accuracy of 8 km (1σ, cross track) and 11 seconds (1 σ, time of closest encounter). '1 his plan is based on ground-commanded T('hi strategy. The last OPNAV image will be sent at E- 12 hr and the last '1 CM executed at E- 6 hr. '1 he two-way light time will be 40 minutes, which will leave about 5 hours to prepare the last '1 CM command from the ground. To limit telemetry volume, on-board image data processing, "windowing," and 2:1 data compression arc planned.

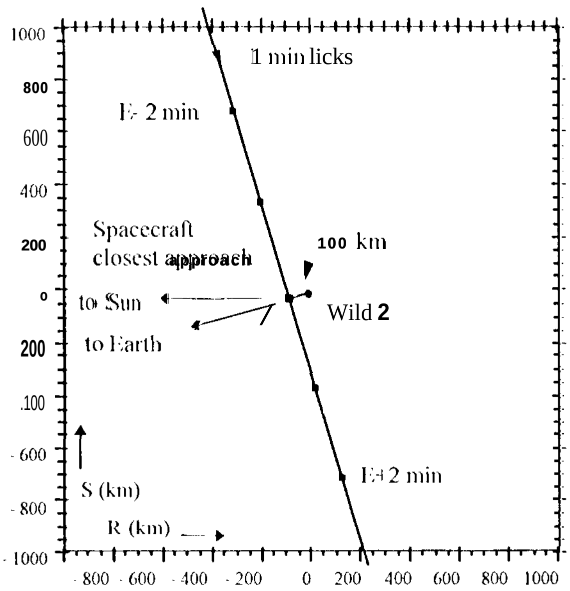

Fig. 4. Orbital Geometry al Closest Encounter, where RS is the orbital plane, R= radial direction, Sun to Wild 2, S orthogonal to R along Wild 2 vel direction.

3../. *3 Encounter Phase Mission Scenarios.* The encounter phase nominally starts at 150 d before aad cads 150 d after comet encounter. Accurate delivery of spacecraft to the desired aim point is accomplished with OPNAV. On-board acquisition of comet images will begin at about E- 15(1 d. (houmi-based image processing and TCM commands are used until E- 1 d. Thereafter, images will be processed on board in order to guide the mirror to contain comet images in the field of view (FOV) of the camera. A mirrored tracking device in the camera system will protect the optics during the coma fly-through and reduce image smear.

To attain low-cost operation, comet imaging goals, being, secondary science, will not dictate the mission scenarios. Instead, imaging science will be acquired as the opportunity permits. '1 he imaging science plan is for all data taken before E- 4 min to be sent back as the OPNAV tracking schedule permits and al] images taken from E- 4 min to E+4 min to be recorded for delayed telemetry.

Only about 100 frames of the highest resolution images scar closest encounter will be recorded, even though the data-link capability)' of the spacecraft (2 kbps/34 m and 8 kbps/70 m) makes it possible to acquire more than this. Spacecraft communications will be with the 34-m high-cfliciency (HEF) stations daring, most of the encounter phase, except for a 30-hr period at closest approach. Continuous tracking by the 70-m stations is planned only during this critical period.

'1 he Encounter Phase begins slowly and builds to an extremely fast pace centered around closest encounter. It is divided into four subphases: Far Encounter, Near Encounter, Close Encounter, and Post-encounter. Far Encounter involves acquisition of comet and coma science data. Near Encounter is the terminal guidance phase, and its science emphasizes high-resolution images of the coma and near-nucleus activities. Close Encounter is the core science period of STARDUST, focused (m collecting samples and imaging the nucleus. Post-encounter is dedicated to assessing mission performance and downlinking comet images.

Fig. 5 shows the timeline of key activities from E-150 d up to closest encounter. This figure also provides the resolution of images and sizes of the coma and the nucleus in the FOV of the camera as a function of time.

3.3.4 Far Encounter Subphase (E-190 d to E-1 d). OPNAV will begin at about E-150 d when Wild 2 becomes detectable. The coma will be the focus of the imaging science during this period. Coma images acquired during this period will have resolutions of 32 to 6000 km per pixel. All eight fillers will be used at each imaging episode and will be sent back at designated OPNAV telemetry time. Approximately thirty 4-111- passes of downlink time will be available during this period. At 1 kbps (50% link capability, 34 m), a data volume amounting to 75 frames of 2:1 compressed images may be sent back. More can be accomplished by combining the onboard "windowing" process. This io essence offers an opportunity to obtain fall color movies of the evolving coma. At E-1 d, the coma image begins to fill the FOV of the camera, and the focus of the imaging will be on the finer details.

3.3.5 Near Encounter Subphase (E-1 d to E-5 hr). STARDUS f' enters the terminal navigation phase with increased OPNAV activities, Continuous communication with Earth (70-m stations) will be established. At E-1 d the OPNAV picture rate will be increased to one per hour. All data acquired since the previous TCM (E-2 d) will be processed on the ground as each image is received for image location extraction, orbit determination, and the final TCM computation. We expect to obtain finer details of coma when we image Wild 2 during this period. The Wild 2 nucleus will still be a pinpoint until the cod of this phase when it begins to occupy about a pixel. Assuming a 50% link capability of the spacecraft, a real-time data volume transmission of 34 image frames with 2:1 compression is possible. Full-color images of

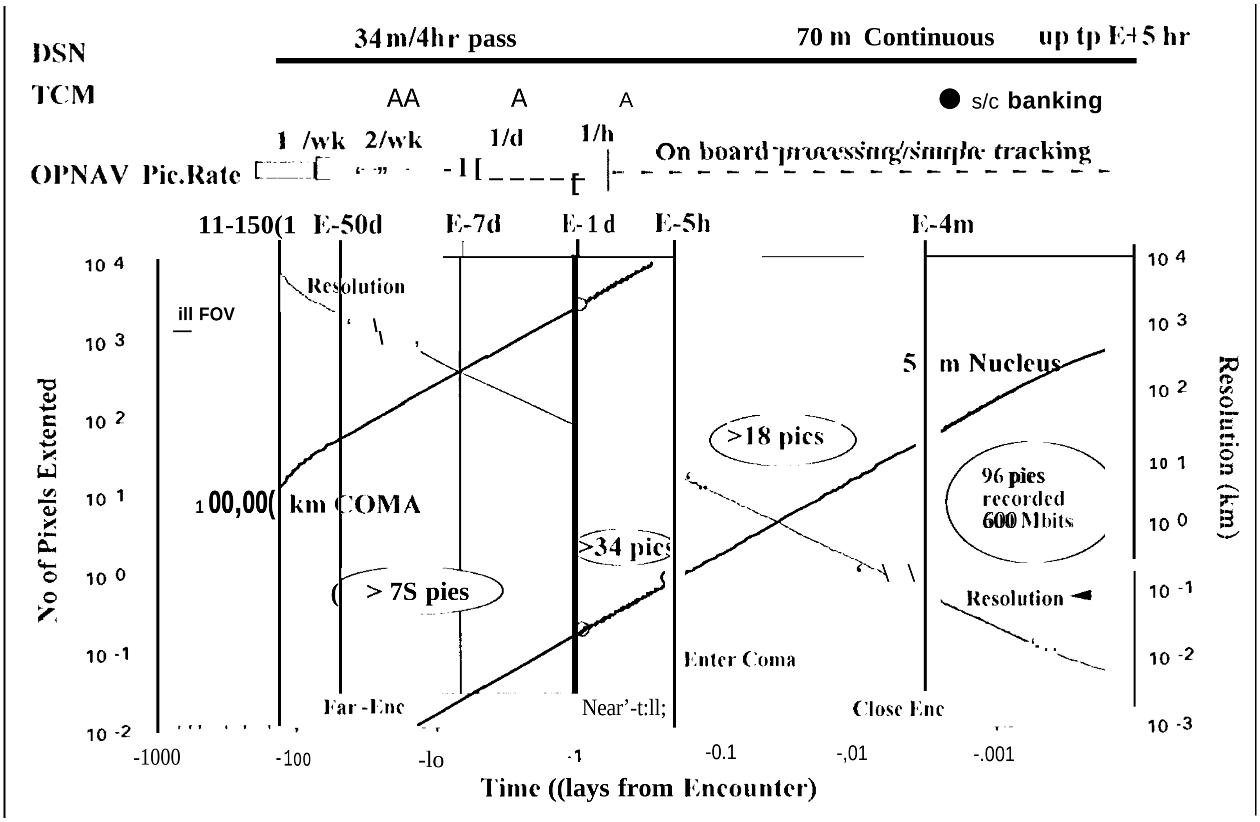

Fig. 5. Mission Timeline for Wild 2 Encounter Phase

Wild 2 with resolutions ranging from S to 32 km per pixel will be obtained during this period.

3.3.6 Close Encounter Subphase (E-5 hr to E+5 hr). This is the core science period of the mission. At E-S hr the spacecraft will begin to enter the coma (100,000 km from Wild 2) and the nucleus will start to emerge as an extended body in the camera FOV. All comet science will be on. Continuous tracking of the spacecraft with the 70-m station is planned until the cad of this mission subphase.

Dust collection will begin with the deployment of the dust collector after the last TCM at E-6 hr. The spacecraft dust shield and the collector array will orient perpendicular to the dust stream (spacecraft-comet relative velocity) to protect the spacecraft from the dust hazard while maximizing the collection area.

CIDA will provide information on comet particle composition during the fly-through. Data from up to 10,000 CIDA events will be compressed and stored on board. The data volume allocated is about 200 Mbits.

Continuous imaging and ml-time transmission of data will be made from 1;- 5 hr to E- 4 min and again from E+4 min to E+5 hr. At E- 4 min when the nucleus occupies 60×60 pixels. a final black and white picture surrounding the nucleus will be sent in real time. This will take no longer than 27 s. Any images taken after E- 4 min will be stored on board. Fig. 6 shows details of mission activities occurring from E- 5 min to E+5 min. Due to the uncertainty in delivery, the image of the nucleus may spill out of the FOV of the camera beginning at about E- 2 min. Although the scanning mirror can compensate for down-track and in-plane errors, only banking the spacecraft (by providing the second axis to the mirror) can correct out-of-plane errors. Because of this, temporary loss of high-gain lock to Earth during the ±3 min of the encounter is expected. The medium gain antenna will take over the critical communications function during this time.

3.3.7 *Post-Encounter Subphase (E+5 hr to E+50 d).* Post-encounter spacecraft health check, reconstruction of flyby conditions and downlink of recorded data will constitute the activities of this mission phase. DSN tracking similar to craisc-phase mode will resume.

3.4 Interstellar Dust Collection Phase Design

3.4.1 Interstellar Grain Impact Profile. Based on recent studies [3], IGs are assumed to enter the heliosphere with a velocity of 30 kms^{-1} from the upstream direction of 10°±10°, 280°±30° ecliptic latitude and longitude. The flight paths of the IGs are modified by solar gravity, solar pressure, electromagnetic interaction with the interplanetary magnetic field, and various other complex processes not well or easily formulated. If one considers only the simple effects of solar gravity and solar pressure, the velocities of IGs of various sizes can be calculated as a function of β, where β is the ratio of solar pressure to solar gravity.

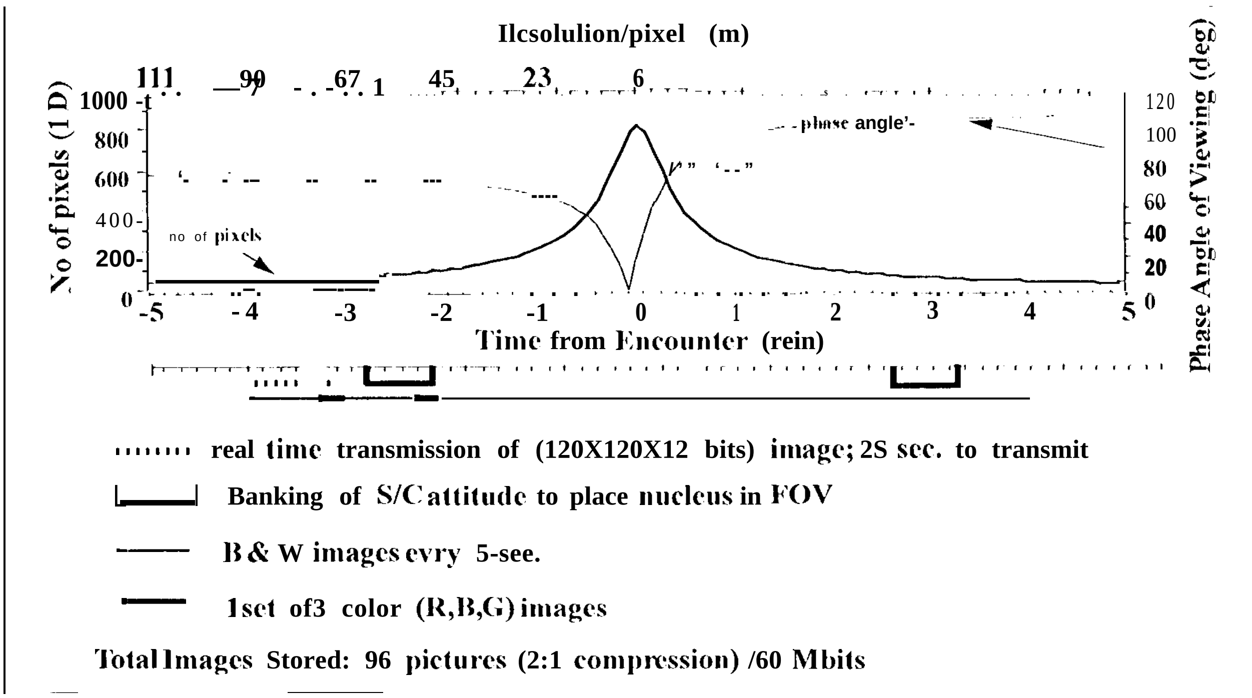

Fig. 6. Timeline During Closest Encounter, E- 5 min. to E+5 min.

Although the IG collector will need to be steered in specific directions to maximize the area for intercepting desired IGs, tight attitude control is not required because the uncertainty in the IG radiant direction may be as large as 30°

3.4.2 Interstellar Grain Collection Strategy. The strategy of IG collection is (1) to collect at tile part of the spacecraft orbit where IG impact velocity is relatively low (<15 kms^{-1}), (2) to orient the collector in a specific direction so that the area for the desired IGs is maximized and the IG tracks indicating normal incidence may be tagged as the desired particle, and (3) to avoid pointing toward the sun in order not to intercept particles of interplanetary origin. Total duration of IG collection will be about 1J% years.

Mission operation during the IG collection period is similar to cruise phase due the passive nature of the collector design.

3.5 Sample Earth Return Phase Design

This phase of the STARDUST mission begins two weeks before Earth re-entry and ends when the SRC is transferred to its ground-handling team. The planned landing site is the Utah Test and Training Range (UTTR). Following touchdown, the SRC will be recovered by helicopter or ground vehicles and transported to a staging area at UTTR for retrieval of the sample canister. The canister will then be transported to the planetary materials curatorial facility at Johnson Space Center.

'1 his Earth Return is divided into four subphases: Earth Approach, Entry, Terminal Descent, and Recovery

3.S, *1 Earth Approach Subphase.* Earth Approach begins with an increased tracking frequency of one 8-hour pass per day. During this pet-iod three TCMs are involved: at ER (Earth reentry) 13 d, ER-3 d and 111<-3 hr. The SRC will be released soon after the last TCM and will enter the atmosphere at a nominal entry angle of -8°. Approach velocity to Earth will be approximately 6.4 kms-1 with a right ascension of **205,7°,** a declination of 11.1°, and velocity at entry (assumed to be at an altitude of 125 km) of 12.8 kms- 1. '1 he entry corridor control accuracy (3s) attainable, based on the Navigation Plan, is 0.08°.

The spacecraft will perform a divert maneuver subsequent to the SRC release to avoid entering the atmosphere.

3.5.2 Entry Subphase. Entry begins when the spacecraft reorients for SRC release from the spacecraft bus and ends with parachute deployment. The SRC will be released from the spacecraft bus approximately 3 bouts before entry. Significant activities during these 3 hours include slewing the spacecraft bus to the proper release attitude, settling and verifying spacecraft attitude, initiating the SRC cm-board timer/sequencer, turning off spacecraft bus provided heater power to the SRC, and releasing the SRC.

'1 he SRC will perform a direct entry at Earth. After entry the SRC will continue to free-fall until approximately 3 km, at which point the parachute deployment sequence will initiate. Elapsed time from entry to parachute deploy will be approximately 10 minutes.

3.5.3 Terminal Descent Subphase. Descent begins when the parachute deployment sequence initiates and continues until the SRC/parachute system has descended into the recovery zone, the UTTR.

'1 he velocity of the SRC must be reduced from the initial entry velocity of 12.8 kms-1 to a level that permits soft landing.

The aeroshell removes over 99% of the initial kinetic energy of the vehicle to protect the sample canister against the resultant extreme aerodynamic heating. The heatshield is a 60° half-angle blunt cone made of a graphite/epoxy composite covered with a thermal protection system. Ablative material on the backshell protects the lander from the effects of recirculation flow around the entry vehicle.

Taking into account SRC release and entry corridor uncertainties, vehicle aerodynamics uncertainties and atmospheric dispersions, the landing footprint ellipse for the SRC has been determined to be approximately 60 km by 6.5 km. The SRC will approach the UTTR on a heading of approximately 122° on a north-west to south-east trajectory. Local time of landing will be approximately 3:00 am.

3.5.4 Recovery Subphase. Recovery begins a few hours before the SRC touches down. Retrieval is via ground transportation or helicopter.

Given the small size and mass of the SRC, it is not expected that its recovery and transportation wi II require extraordinary handling measures or hardware other than a specialized handling fixture to cradle the capsule during transport.

Transportation of the SRC to a staging area at the UTTR for extraction of the sample canister will follow. The sample canister thca will be transported to its final destination, the planetary material curatorial facility at Johnson Space Center.

4. FLIGHT SYSTEM DESIGN

The STARDUST flight system is composed of the sample return capsule (SRC) and the spacecraft. Each employs elements of advanced technology in concert with flight-proven components to produce a cost-effective, lightweight spacecraft capable of operating reliably in deep space for long-duration missions. Designed from the ground up with cost and mass-efficiency in mind, the STARDUST flight system represents a new wave of mail, lightweight spacecraft. Although STARDUST is representative of the new approach to *faster, better, cheaper*, it still embodies Lockheed-Martin 's total commitment to mission success. STARDUST has been designed to eliminate all credible single-point failures from the system.

I'repulsion on STARDUST depends on a single, simple, blowdown hydrazine system. The mission has been designed with minimal AV requirements and very loose attitude-control requirements for the bulk of the mission. Therefore a single-tank monopropellant system is adequate to meet the propulsion requirements of STARDUST

The telecommunications system on STARDUST consists of fully redundant X-band [iccp-space transponders, solict-slate power amplifiers, and associated filters, couplers, switches, and waveguides. During comet encounter, the period of highest demand on telecommu nications data rate, tile geometry between comet, spacecraft, and Earth do not change significantly. Exploiting this fact, the STARDUS 1' high-gain antenna is fixed-mouatcci without a gimbal mechanism, thereby saving cost, complexity, and mass. During tile remainder of the mission, when the attitude of tile spacecraft is not held within tight deadbands, communications are through a medium-gaia antenna. Low-gain patch antennas arc also integrated into the telecommunications system for use during the initial ization and checkout phase of the mission and, if necessary, during safing modes.

Power for STARDUST (some 26(I W at encounter) is provided by two solar arrays each covering 3 m^2. Each solar array is also fixed-mounted to the bus. Power conditioning, control, and distribution functions arc provided by advanced avionics cards developed by LMA for deep space missions. Commonality of the electrical power system among several ongoing spacecraft programs at LMA provides a cost-effective strategy for implementing s(atc-of-the-zirt avionics. The SMTS evolutionary test plan will concurrently integrate analysis, design, and testing to achieve high confidence in mission success.

Command and Data Handling (C&DH) for STARDUS 1' is essentially inherited and includes advanced circuitry now being developed for a number of ongoing programs at LMA. The central processor card is an R6000 with 1 Gbit of on-card sol id-stale data-storage capacity. Interfaced to the processor card through a VME bus are the data I/O cards, payload